Transport Canada
Transports Canada

Development
Développement

TP 4843E

MM

Sodium Heat Pipe Design for Stirling Engines

Final Report

Prepared for the
Transportation
Development Centre
Transport Canada

July 1983

CA1
DTC 801
83
S53
c.2

Canada

B&D

TP No. 4843E

SODIUM HEAT PIPE DESIGN

FOR STIRLING ENGINES

Library and Information Centre / Centre de Documentation (GSLA)
RECEIVED – REÇU LE
DEC 14 1983
Transport Canada / Transports Canada

FINAL REPORT

JULY 1983

TRANSPORT CANADA

TRANSPORTATION DEVELOPMENT CENTRE

WHITEGAITES ENGINEERING LTD.

CALGARY, ALBERTA

REPORT DOCUMENTATION FORM

1. Transport Canada Report No.	2. TDC Project No.	3. Recipient's Catalogue No.
TP 4843E		

4. Title and Subtitle	5. Report Date
Sodium Heat Pipe Design for Stirling Engines	July 1983
	6. Performing Organization Report No.

7. Author(s)	8. Transport Canada File No
Graham Walker	D1465-323-2

9. Performing Organization Name and Address	10. DSS File No.
Whitegaites Engineering Ltd. 4023 Vardell Rd. N.W. Calgary, Alberta, T3A OC3	11. DSS or Transport Canada Contract No TDC 4907

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Transportation Development Centre 1000 Sherbrooke St. W. Montreal, Quebec, H3A 2R3	1 Jan./30 June 1983
	14. Sponsoring Agency Code

15. Supplementary Notes	16. TDC Project Officer
	Richard F. Dillon

17. Abstract

A heat pipe is a device for transferring heat with minimum loss and temperature difference from a thermal source to a thermal sink. Heat pipes are proposed for application to transfer heat from a fluidised bed coal combustor to the heater head of a Stirling engine. Two stage multi-tube heat pipes with sodium metal-working fluid are preferred. However there is little established experience of large sodium heat pipes and none at all of two stage systems.

A design for a single tube two stage heat pipe of 10 kW thermal capacity was prepared and techniques and procedures were devised for its fabrication and test. This was undertaken as an exercise to acquire the technology for large two stage systems. Fabrication and test of the unit are recommended to gain practical experience and investigate the various problem areas likely to be encountered.

18. Key Words	19. Distribution Statement
Stirling, Engine, Sodium, Heat, Pipe	Unlimited

20. Security Classification (of this report)	21. Security Classification (of this page)	22. No. of Pages	23. Price
None	None		

TDC/CDT 79-005

FORMULE DE DOCUMENTATION POUR RAPPORT

1. N° du rapport Transports Canada	2. N° de l'étude — CDT	3. N° de catalogue du destinataire
TP 4843E		

4. Titre et sous-titre	5. Date du rapport
Sodium Heat Pipe Design for Stirling Engines	July 1983
	6. N° du rapport de l'organisme exécutant
7. Auteur(s)	8. N° de dossier Transports Canada
Graham Walker	D1465-323-2
9. Nom et adresse de l'organisme exécutant	10. N° de dossier — ASC
Whitegaites Engineering Ltd. 4023 Vardell Rd. N.W. Calgary, Alberta, T3A OC3	11. N° de contrat — ASC ou Transports Canada TDC 4907
12. Nom et adresse de l'organisme parrain	13. Genre de rapport et période visée
Transportation Development Centre 1000 Sherbrooke St. W. Montreal, Quebec, H3A 2R3	1 Jan./30 June 1983
	14. Code de l'organisme parrain
15. Remarques additionnelles	16. Agent de projet — CDT
	Richard F. Dillon

17. Résumé

Un caloduc est un appareil qui sert à transporter la chaleur produite par une source thermique jusqu'au lieu d'utilisation, avec un écart de température et des pertes calorifiques minimunes. Des caloducs sont envisagés pour transmettre la chaleur produite dans une chambre de combustion utilisant du charbon sur lit fluidisé, jusqu'à la chambre chaude d'un moteur à cycle de Stirling. Des caloducs multitubes à deux circuits contenant du sodium agissant comme fluide caloporteur sont préconisés. Nos connaissances en matière de caloducs à sodium de grandes dimensions sont faibles, et inexistantes dans le cas de caloducs à deux circuits.

Il a fallu etudier un caloduc à un tube et à deux circuits d'une capacité thermique de 10 kW, élaborer une technique de fabrication et mettre au point des méthodes d'essai. Cette étape a permis d'acquérir les connaissances nécessaires à la réalisation d'un système à deux circuits, de grandes dimensions. Le rapport recommande de procéder à la fabrication et l'essai d'un caloduc de ce type, de manière à accumuler l'expérience nécessaire et cerner les aspects épineux de la question.

18. Mots-clés	19 Diffusion
Moteur à cycle de Stirling, Caloduc, Vapeur de sodium	Unlimited

20. Classification de sécurité (de ce rapport)	21. Classification de sécurité (de cette page)	22 Nombre de pages	23 Prix
None	None		

CDT TDC 79-005

FOREWORD

A survey of the technology of sodium heat pipes was made. Subsequently the design of a two stage, single tube heat pipe of 10 kW thermal capacity was made and techniques for its fabrication and testing were devised. The work was carried out during the period January 1 and June 30, 1983 on behalf of the Transportation Development Centre, Department of Transport, Montreal. Mr. Richard Dillon, Senior Project Officer of TDC, was the designated Scientific Authority for the work.

G. Walker
Principal Investigator

Calgary, Alberta

July 1983

LIST OF CONTENTS

	Page
TITLE PAGE	i
REPORT DOCUMENTATION FORM	ii
FOREWORD	iv
LIST OF CONTENTS	v
LIST OF FIGURES	vii
1.0 INTRODUCTION	1
2.0 GENERAL DESIGN CONSIDERATIONS	3
2.1 Fluidised Bed Coal Combustor	3
2.2 Sodium Heat Pipe	4
2.3 Design Guidelines	6
2.4 Two Stage Heat Pipe	6
2.5 Gas Ballasted or Variable Conductance Heat Pipe	8
2.6 Heat Pipe Materials	11
2.7 Welding and Joining	12
2.8 Sodium Metal	12
2.9 Heat Pipe Filling	13
2.10 Heat Pipe Literature	13
3.0 DESIGN OF PROTOTYPE TWO STAGE, SINGLE TUBE TEST UNIT AND ASSOCIATED TEST EQUIPMENT FOR 10 kW HEAT TRANSMISSION	14
3.1 Principal Dimensions	21
3.2 Heat Input	24
3.3 Thermal Insulation	25
3.4 Wick Structure	25
3.5 Gas Ballast Reservoir	26

		Page
3.6	Instrumentation	27
4.0	TEST AND EVALUATION PROCEDURE	27
4.1	Fabrication	27
4.2	Cleaning	28
4.3	Filling	28
4.4	Seasoning	28
4.5	Testing	29
4.6	Problem Areas	29
5.0	CONCLUSION	30
REFERENCES		31
APPENDICES I:	Rice, G. and Jennings, T., Heat Pipe Filling, Proc. 1st International Heat Pipe Conf., Stuttgart, F.R. Germany	32
II:	Calculation of Sodium Mass	44

LIST OF FIGURES

		Page
Figure 1	General Arrangement of Two Stage Single Tube Sodium Heat Pipe	15
Figure 2	General Arrangement of Test Apparatus	16
Figure 3	Detail of First Stage Evaporator Assembly	17
Figure 4	Detail of First Stage Evaporator	18
Figure 5	Detail of Cross Tube Assembly	19
Figure 6	Detail of Condenser Sections	20

1.0 INTRODUCTION

A previous report (Walker, 1980)*, assessed the possibilities for Stirling engines in railway locomotives using coal and other alternative fuels.

The report included proposals for novel Ringbom-Stirling engine arrangements based on the conversion of diesel engines and using air working fluid and water lubrication. Such engines were to be energised by coal in fluidised bed combustors with a sodium heat pipe effecting transfer of the combustion heat to the engine. The engines were intended to drive electric power generators for energising the propulsion wheel motors of the locomotive.

A contract for the provision of a small demonstration engine incorporating all these features was negotiated between the Government of Canada and the University of Calgary commencing August 1, 1981. The contract specified the work to be done in sequential phases:

1) Design of prototype demonstration only.
2) Fabrication and test of prototype engine using any convenient heat source.
3) Design, fabrication and independent test of
   a) a fluidised bed coal combustor,
   b) sodium heat pipe,
   of a size appropriate for integration with the prototype engine.
4) Integration of the engine with the coal combustor and sodium heat pipe. Performance test of the integrated unit.
5) Design of full-scale locomotive engine.

---

* References are listed in full at the end of the report.

Phase 1 of the contract was completed in late 1981[3] and Phase 2 was carried out at the University of Calgary in 1982 and 83.

In late 1982 general proposals for undertaking the Phase 3 work were prepared by the University of Calgary including an outline design of the prototype fluidised bed combustor and the associated sodium heat pipe.

The heat pipe proposed was a two stage system of 12 first stage heat pipes partially immersed in the fluidised bed and conveying heat from the bed to the interface of the first and second stages. The purpose of the single second stage heat pipe was to convey heat to the heater head of the engine.

The heat pipe unit having an overall net thermal capacity of 120 kW approached the limit of established metal heat pipe practice. Moreover although the concept of two stage heat pipes was well known there was no well developed body of operational data available. Finally the University of Calgary had no established experience in the field of high temperature heat pipes.

It was therefore deemed appropriate to introduce some additional work, preliminary to Phase 3 of the above referenced contract, concerned with the design and the procedures for manufacture and test of a two stage sodium heat pipe having single tube first and second stages, a 10 kW thermal transfer capacity and of a size generally compatible with the 12 tube, 120 kW unit proposed earlier for the prototype engine/fluidised bed/heat pipe combination.

This report is the product of that auxiliary study and contains:

a) the outline engineering design of the two stage, single tube heat pipe design,

b) the associated manufacturing and test fixtures and equipment,

c) procedures for manufacture and testing the unit.

2.0 GENERAL DESIGN CONSIDERATIONS

A fluidised bed coal combustor and heat pipe system was proposed by the University of Calgary for the above referenced contract. This included a two stage sodium heat pipe with 12 first stage tubes contained within the general envelope of the proposed fluidised bed combustor.

2.1 Fluidised Bed Coal Combustor

Briefly the design parameters adopted to determine the fluidised bed geometry were as follows: (after Barton and Holcomb, 1982):

Minimum bed depth - 1.2 m

Minimum disengagement height - 1.2 m

Minimum freeboard - 2 x bed depth = 2.4 m

Fluidising velocity of the air at the distribution plate - 0.5/0.6 m/sec

Limiting power density of bed - 0.5 MW/m^2

Limestone feed rate - 4 mols calcium per 1 mol sulphur supplied in coal for 90 percent sulphur removal

Bed area per coal feed nozzle - 1 m^2

The maximum required output from the Stirling engine is 20 kW. A maximum heat release in the fluidised bed of 5 times engine output = 100 kW was assumed. The required bed volume was then: $\frac{100}{500} = 0.2\ m^3$. Assuming a cubic form of bed the length of side is 0.58 m (22.8 ins).

However the minimum recommended bed depth is 1.2 m (47.2 ins). Therefore assuming a square section bed of 0.6 m side and 1.2 m depth the bed volume is 0.6 x 0.6 x 1.2 = 0.43 m^3, over twice the minimum

required bed volume.

The minimum disengagement height is 1.2 m and the minimum upper and lower plenum heights are each 0.2 m approximately. The minimum height of the fluidised bed is then 1.2 + 1.2 + 0.2 + 0.2 = 2.8 m. This vertical height can be comfortably accommodated within the vertical installation envelope of existing railway locomotives. There is, therefore, no need to contemplate horizontal or inclined operation of the fluidised bed.

2.2 Sodium Heat Pipe

The sodium heat pipes serve to transfer heat from the fluidised bed coal combustor to the Stirling engine heater. They are used because they can transfer large amounts of heat with a very small temperature drop and at the temperature levels of 700 to 800°C required by the Stirling engine. In the most elementary form a heat pipe consists of a simple tube closed at both ends and comprising three sections:

a) the boiling section wherein heat drawn from the fluidised bed vaporises sodium in the tube.

b) the condensing section wherein sodium vapour in the tube condenses on the wall of the tube or on the heater tubes or heater head of the Stirling engine with transfer of heat from the condensing sodium to the tube walls.

c) the adiabatic section wherein sodium vapour passes from the boiling section to the condensing section and sodium liquid passes from the condensing section to the boiling section. To a first approximation there is no heat transfer between the sodium and the tube walls of the heat pipe in the adiabatic section.

Maximum heat transfer is achieved with a vertical heat pipe arranged so the boiling section is below the condensing section. With this arrangement gravity ensures that the heavy liquid condensate returns to the boiling section. The downward flow of liquid is along the walls of the heat pipe and the upward flow of vapour takes place through the centre 'core' of the heat pipe.

In many vertical heat pipe situations the natural gravity-induced fluid flow is sufficient to eliminate the need for the additional flows that may be gained by utilising surface tension forces with a 'wick' of wire screen, fine bore tubes or narrow channels in the direction of the return liquid flow (from condensing to boiling sections).

Heat pipes with no internal work systems are called 'thermosyphons'. They can only be used when the condensing section is *above* the boiling section and depend for their action on the difference in density of the liquid and vapour fractions of the fluid in the heat pipe.

There appears to be no conceivable situation in the locomotive application where the vertical heat pipe with the condensing system uppermost *cannot* be used. Therefore it is most likely that on grounds of simplicity, reliability and cost thermosyphons will be favored.

A partial wick, in the boiling section, will be necessary to ensure 'wetting' of the walls of the heat pipe immersed in the fluidised bed. The alternative, a sodium inventory in the heat pipe sufficient to fill the tube to the extent of immersion in the bed would be grossly uneconomic.

The principal limitation to heat transfer is the convective transfer from the bed medium to the outer walls of the heat pipe. To maximise the area for heat transfer it may be anticipated the heat pipe

will be immersed in the bed to the maximum depth (a minimum of 1.2 m) and the immersed length will be the length of the boiling section.

Immersion of the heat pipe in the bed to the maximum depth has a compelling practical advantage that the lower free end of the heat pipe may be physically secured to the distribution plate to minimise the vibration induced by motion of the bed media.

2.3 Design Guidelines

Dunn *et al* (1975) indicate that heat transfer rates of 100 kW/m^2 of heat transfer surface may be attained with fluidised combustors and that bed power densities of 650 kW/m^3 may be achieved. Similarly they suggest that heat fluxes (along the tube from the boiling to the condensing sections) of 15 kW/cm^2 of heat pipe tube cross-section area may be achieved.

Rice (1983) recommends design heat fluxes between the tube wall and the sodium of 40 $watts/cm^2$ in the boiling section and 150 $watts/cm^2$ in the condensing section.

2.4 Two-Stage Heat Pipe

In operation the media of a fluidised bed experiences a considerable and complex motion. Tubes or other surfaces immersed in the bed rapidly assume a burnished appearance and there is some concern that the tube may suffer high rates of wear. No definitive work about the aspect of fluid bed operation was found in the literature but proposals have been made to apply hard ceramic coatings to the exterior surfaces immersed in the bed to minimise the wear rate. Application of a ceramic coating would unfortunately increase the thermal resistance to heat transfer at precisely the area of greatest thermal resistance.

With a high capacity fluidised bed and heat pipe combination it is to be expected that a large number of relatively small diameter heat pipes would be immersed in the bed. Leakage of sodium from any of the tubes resulting perhaps from high rates of wear, defective material or another cause would result in the sodium contained in the heat pipe entering the bed and being consumed therein. If all the heat pipes were mutually coupled a leak in one of the tubes could result in loss of the entire sodium inventory.

To eliminate the possibility, given the hostile environment of the fluidised bed, the proposal has been made for a two stage heat pipe. In this concept multiple first stage heat pipes are immersed vertically in the bed. They are mutually independent and serve simply to convey heat from the boiling section in the bed to their own condensing section in the disengagement zone above the bed. A leak or material failure in any of these multiple first stages results in the loss of sodium in that tube but leaves the remainder intact. Thus with 100 tubes the failure of as many as 30 tubes would leave the system capable of 70 percent full load. In practice the remaining tubes would assume some of the duty of the failed tubes to increase the availability to perhaps 85 percent of design capacity.

The mutually independent first stage heat pipes would be combined with a second stage heat pipe having the duty of conveying heat from the area of the condensing sections of the first stage tubes (the boiling section of the second stage heat pipe) to the heater or heater head of the Stirling engine (the condensing section of the second stage heat pipe).

No reports of actual operating experience or experimental work

with two stage heat pipes were found in the literature. There appears to be no technical limitation to operation as described above. It is thought the absence of references is due to the fact that no applications of two stage heat pipes have been made. The elements of the two stage heat pipe are, simply, two single stage units combined. The fact that multiple versions of the first stage units are combined with a single version of the second stage unit has no significant effect on operation. Difficulties may arise in ensuring a proper distribution of the second stage condensate to the multiple, parallel, second stage evaporative sections.

For locomotive and other Stirling engine applications it is likely that the engine heater would be appreciably above the disengagement zone of the fluidised bed and gravity could be relied on to return the liquid sodium from the condensing section (the engine heater) to the boiling section (the first stage/second stage interface in the bed disengagement zone).

2.5 Gas Ballasted or Variable Conductance Heat Pipe

In its simplest form a heat pipe consists of a hollow tube closed at both ends and containing a working fluid (sodium) in the solid, liquid, or vapor phase. Without heating the sodium will be entirely in the solid phase with a very small vapour pressure of sodium vapour in the remaining space. Sodium melts to liquid on heating to about 100°C. Thereafter as further heat is supplied the temperature and vapour pressure increase. At 500°C the vapour pressure is 0.01 bar and increases to 0.47 bar at 800°C and 2.81 bar at 1000°C.

The addition of a gaseous compoment (argon, an inert gas with a low thermal conductivity is preferred) to the single component heat pipe

described above creates a 'gas ballasted' or 'variable conductance' heat pipe. In the normal operation of a vertical gas ballasted heat pipe heat enters through the walls of the boiling section at the lower end of the tube and vaporises liquid sodium contained in the 'wick'. The vapour ascends the tube and condenses on the walls of the condensing section above the boiling section.

The argon gas accumulates in the reservoir and the 'thermal dump' located above the condensing section at the upper part of the heat pipe. It plays virtually no part in the heat transfer process. The location of the interface separating the sodium and the argon depends on:

a) the mass of argon in the heat pipe,

b) the vapour pressure (and hence the temperature) of the sodium.

As the rate of heat transfer to the boiling section is increased (or decreased from the evaporating section) the sodium temperature and vapour pressure increases causing some compression of the argon squeezing it to a smaller volume. The interface separating the sodium and argon ascends and thereby increases the length of the condensing section of heat pipe.

This characteristic movement of the gas/vapour interface provides a virtually fool-proof, fail-safe automatic control system for the Stirling engine application subject to sudden load changes. Consider for example the situation arising when the engine is suddenly and unexpectedly shut-down or completely unloaded either by mechanical failure, seizure or sudden reduction in the load demand.

The coal feed to the fluidised bed would of course be shut down virtually simultaneously with the change in engine demand but the coal

already in the bed will continue to burn and supply heat to the heat pipes immersed in the bed. If the rate of heat removed from the heat pipe in the condensing section is greatly reduced the inevitable result is that heat is accumulated in the heat pipe with the concomitant result that the temperature and vapour pressure levels increase (and markedly so because the thermal capacity is relatively low).

The strength of the metal tubes containing the sodium declines with increase in temperature and the combination of increased pressure and decreased strength may result in a rupture of the heat pipe with escape of the sodium. This potentially dangerous situation can be avoided with a gas ballasted heat pipe. In the unusual circumstance following sudden cessation of the load demand the tendency to increased temperature levels carries the sodium vapour/argon gas interface into the 'thermal dump' region of the heat pipe where the excess heat can be dissipated. In normal operation this is occupied entirely by the argon gas and is virtually inactive.

In the two stage heat pipe proposed for the coal-burning Stirling engine it is necessary that the individual first stage units be gas ballasted systems rather than the second stage unit. This covers the hazardous situation arising from a failure by leakage of the second stage system.

It is not necessary to design the second stage system as a gas ballasted heat pipe but this is desirable for reasons other than safety. Practical experience has shown that the very high purity and cleanliness requirements for heat pipe systems may be substantially relaxed for gas ballasted systems. The various contaminants causing a serious deterioration of thermal performance of a non-ballasted heat pipe, appear to accumulate with little deleterious effect in the

gas ballast volume.

In practical railway engineering any path is attractive if it leads to relaxation of the cleanliness and purity requirements.

2.6 Heat Pipe Materials

The thermal efficiency of Stirling engines depends principally, as with all heat engines, on the maximum (heater) and minimum (cooler) temperature. The efficiency increases, albeit at a progressively diminishing rate, with increase in temperature. However, the mechanical strength of metals decreases with temperatures and fatigue strength and corrosion characteristics are also important. The cost and difficulty in fabrication of metals for high temperature use increases with maximum temperature. The eventual application of ceramic components for high temperature use may be anticipated.

In this complex and multi-faceted situation use of the 18/8 stainless steels for the heater components of large Stirling engines is foreseen in the immediate future. They have the most favourable combination of mechanical strength, cost, ease of fabrication and joining, availability and corrosion resistance. The marked decline in mechanical strength of 18/8 stainless steels at temperatures above 750°C limits the maximum engine temperature to this value.

Experience has shown that sodium, a highly reactive metal in the presence of air and water, is compatible with the 18/8 stainless steels provided proper standards of cleanliness and preparation of surfaces are maintained. Type 316 stainless steel has been found suitable for combination with sodium and is the material of choice on grounds of cost, wide availability in many different forms and components, ease of fabrication, machining and joining.

To avoid problems arising from the use of mutually incompatible materials, or of different electromotive potentials it is recommended that no materials other than type 316 stainless steels be used for the heat pipe and associated equipment.

For industrial application the heat pipe would be welded closed following charging with sodium metal and argon gas. However, for experimental units future access may be required and can be gained by incorporating a valve (rated for vacuum service) in the upper gas-filled, ambient temperature region of the heat pipe assembly.

2.7 Welding and Joining

For sodium heat pipes the only satisfactory method of joining parts is by welding. High quality welds effected by tungsten inert gas (TIG/Argon arc) or electron beam welding is preferred to minimise occlusions and contamination leading to corrosion and internal chemical attack.

2.8 Sodium Metal

Sodium metal is available with very high purity in glass ampoules from the scientific supply companies. This is scientific grade sodium and is suitable for use in small, non-ballasted systems where very high standards of purity are required.

Economic considerations dictate the use of industrial grade sodium where possible. This is supplied as a 'cake' or 'cheese' in containers filled with kerosene. In some cases the cheese is covered with a 'rind' of unknown composition, probably sodium oxide. This can be removed by paring with a conventional kitchen knife to expose the white shiny metal below. This process must be carried out in an argon-

filled glove box or with the metal under kerosene to preclude the possibility of contact with air or water.

In other cases the sodium metal bars are wrapped in heavy duty plastic, aluminum foil, or, for aluminum foundry use, encapsulated in aluminum 'lozenges'.

A good compilation of data about sodium, its properties, laboratory techniques for handling and the corrosion characteristics of various materials with sodium may be found in the Liquid-Metals Handbook prepared by Lyon *et al* (1952).

2.9 Heat Pipe Filling

Rice and Jennings (1973) described the techniques and procedures developed at the University of Reading for cleaning, preparing, filling and sealing sodium heat pipes. This paper is reproduced in Appendix 1 and is the procedure proposed for the prototype unit outlined herein.

2.10 Heat Pipe Literature

The international literature of heat pipes is very extensive. An excellent summary of the fundamentals of heat pipes and their applications, including sodium heat pipes used in conjunction with Stirling engines was given by Asselman and Green (1973 a and b). Their work was principally directed to Stirling engine applications as part of the long and extensive Philips programme of Stirling engine development. The two articles referenced above rank as the literature most relevant to this project. Later Asselman (1976) reported further studies of fluidised bed coal combustion to energise a Stirling engine using a sodium heat pipe.

Another reference of particular relevance is the summary paper of Dunn *et al* (1975) and the associated thesis by Thring (1979) describing research at the University of Reading on the combination of a propane fuelled fluidised bed/sodium heat pipe and Stirling engine.

The principal reference work on heat pipes is the classic work by Dunn and Reay (1978). This could be regarded as the summary volume of another primary source of information, the series of proceedings of the international heat pipe conferences held at approximately 3 year intervals, Stuttgart 1973, Bologna 1976, Palo Alto 1978, London 1981 and scheduled for Tsukuba, Japan in 1984.

An extensive compilation of the engineering design data and procedures for heat pipes generally are the series of publications of the Engineering Sciences Data Unit, London. The folio numbers 79012, 79013, 80013, 80017 and 81038 (E.S.D.U. 1979/80/81) are particularly relevant.

3.0 DESIGN OF PROTOTYPE TWO STAGE, SINGLE TUBE TEST UNIT AND ASSOCIATED TEST EQUIPMENT FOR 10 kW HEAT TRANSMISSION

Figures 1 through 6 shows the proposed single tube, two stage prototype sodium heat pipe. The energy flow as follows:

a) 10 kW input to the first stage involving *convective heat transfer* from the fluidised bed or molten metal bath to the tube wall, *conductive heat transfer* through the tube wall and boiling heat transfer from the tube wall.

b) 10 kW output from the first stage by *condensing heat transfer* to the tube wall, *conductive heat transfer* through the tube wall and *boiling heat transfer* from the tube walls to the second stage tube contained within the upper part of the first

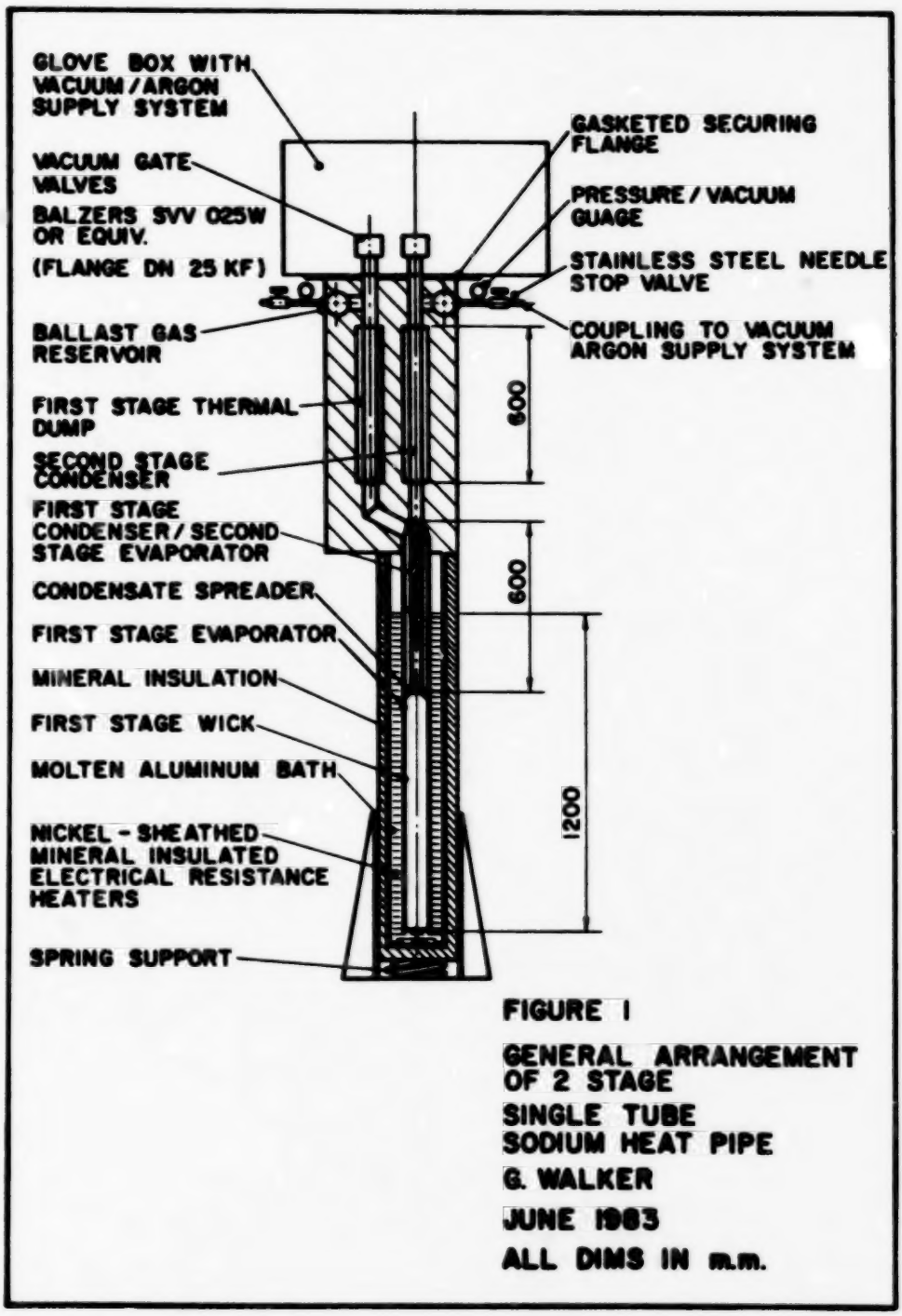


Figure 1 General Arrangement of Two Stage Single Tube Sodium Heat Pipe

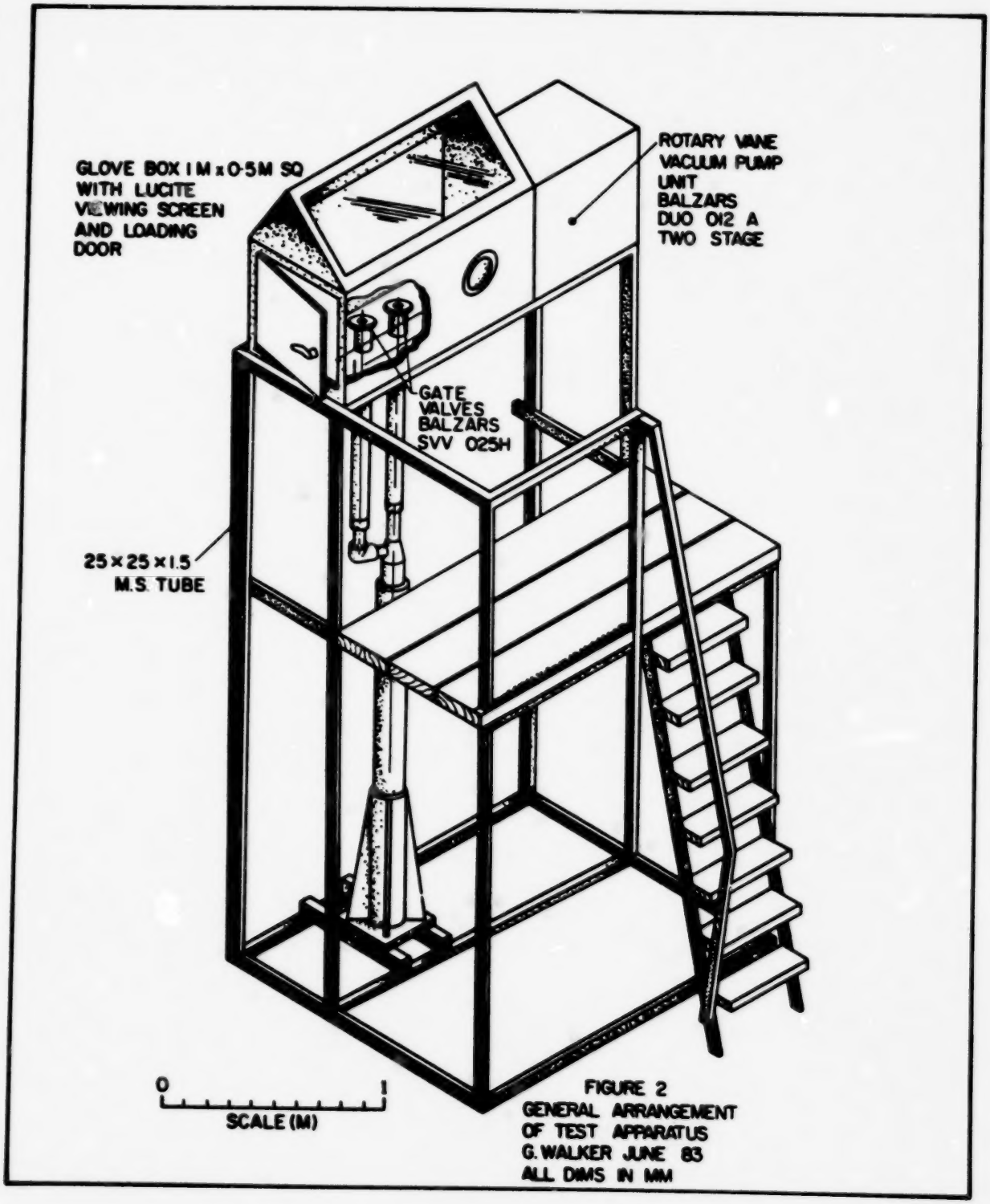


Figure 2 General Arrangement of Test Apparatus

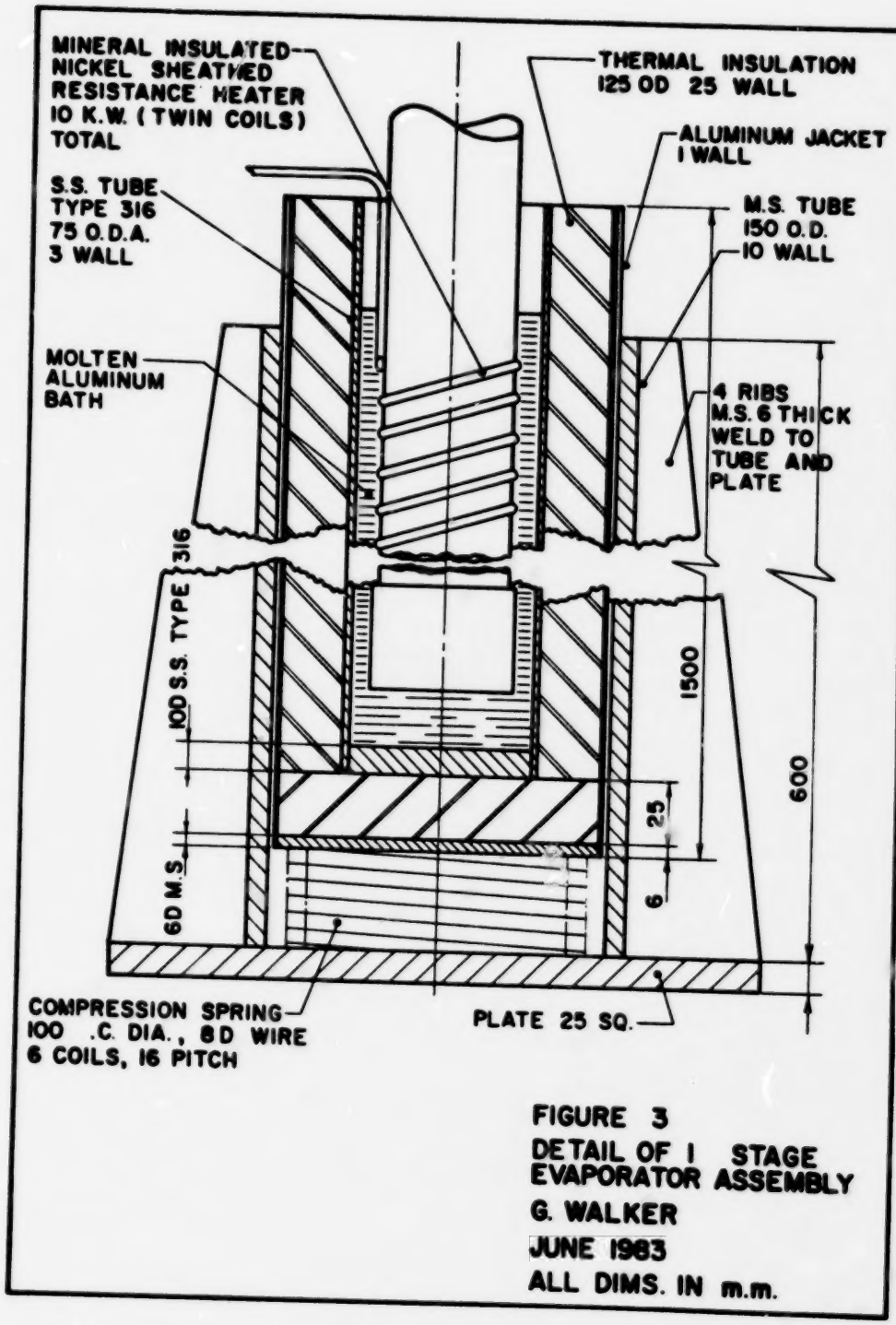

MINERAL INSULATED NICKEL SHEATHED RESISTANCE HEATER 10 K.W. (TWIN COILS) TOTAL
S.S. TUBE TYPE 316 75 O.D.A. 3 WALL
MOLTEN ALUMINUM BATH
THERMAL INSULATION 125 OD 25 WALL
ALUMINUM JACKET 1 WALL
M.S. TUBE 150 O.D. 10 WALL
4 RIBS M.S. 6 THICK WELD TO TUBE AND PLATE
100 S.S. TYPE 316
60 M.S.
1500
600
25
6
COMPRESSION SPRING 100 .C. DIA., 8 D WIRE 6 COILS, 16 PITCH
PLATE 25 SQ.
FIGURE 3
DETAIL OF 1 STAGE EVAPORATOR ASSEMBLY
G. WALKER
JUNE 1983
ALL DIMS. IN m.m.

Figure 3 Detail of First Stage Evaporator Assembly

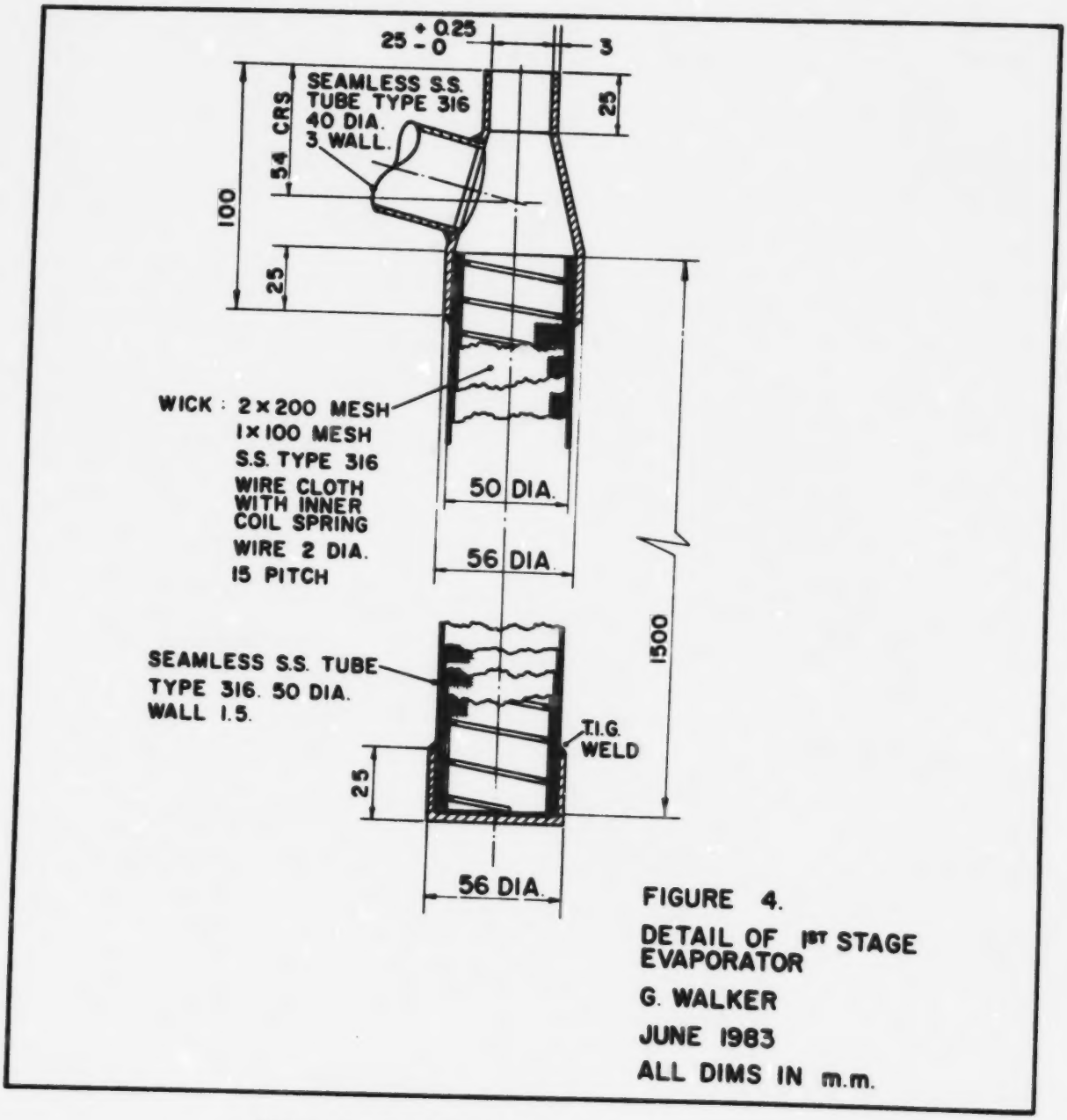


Figure 4 Detail of First Stage Evaporator

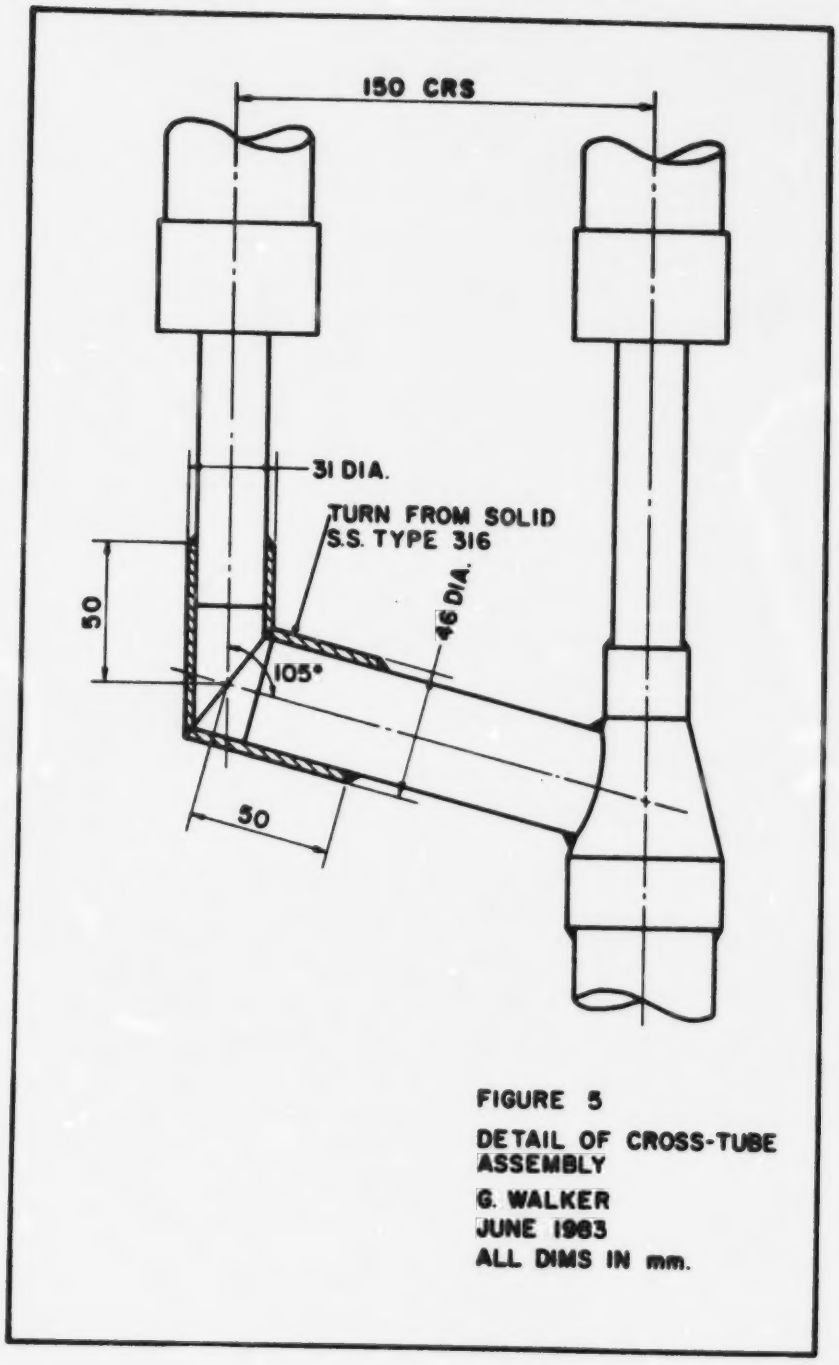


Figure 5 Detail of Cross Tube Assembly

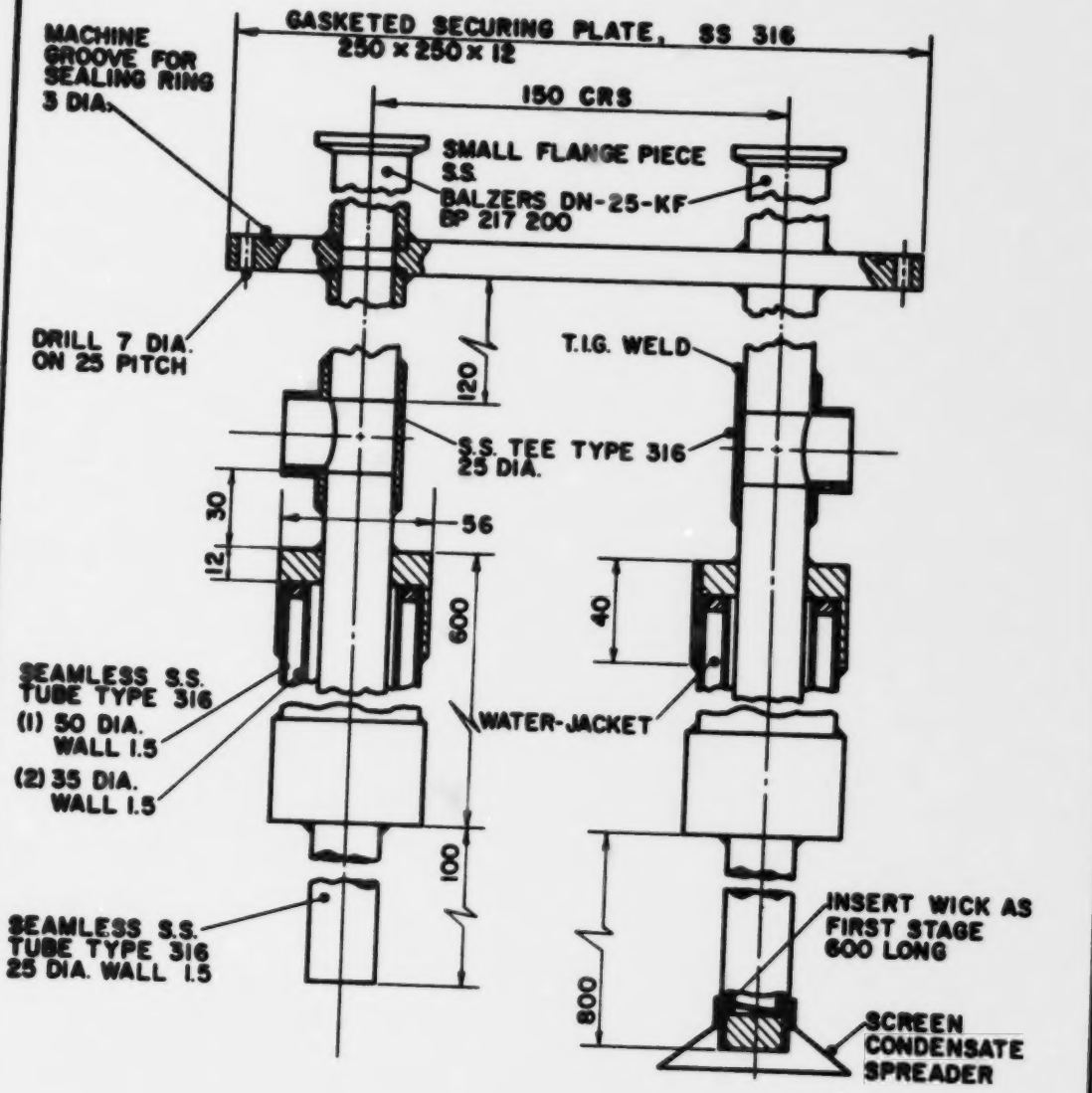


FIGURE 6
DETAIL OF CONDENSER SECTIONS
G. WALKER
JUNE 1983
ALL DIMS IN MM

Figure 6 Detail of Condenser Sections

stage tube.

c) 10 kW heat transmission from the boiling section to the condensing section through the adiabatic section of second stage.

d) 10 kW output from the second stage by condensing heat transfer to the tube wall, conductive heat transfer through the tube and convective heat transfer from the tube walls to the cooling water.

e) 10 kW thermal dissipation in air cooled convective heat transfer heat exchanger, an adapted automobile radiator.

f) Alternative thermal dissipation to the water coolant may be achieved through the gas ballast thermal dump of the first stage.

3.1 Principal Dimensions

a) Heat Transfer, Fluidised Bed to Tube Wall

Assume: i) first stage to be stainless steel, type 316 tube, thin wall, 5 cms outside diameter,

ii) burial depth in bed is 1.2 meters,

iii) limiting heat flux, bed to tube wall, 100 kW/m^2.

Surface area of immersed tube $A_b = \pi \times 0.05 \times 1.2 = 0.1884\ m^2$.

Thermal flux $Q_w = 10/0.1884 = 53\ kW/m^2$ from bed to tube. This is approximately half the limiting value of 100 kW/m^2.

b) Boiling Heat Transfer, First Stage

Assume: i) wetted length of tube (inside is equal to depth of immersion in bed, i.e. 1.2 m,

ii) inside tube area is equal to outside tube area (approximately true for thin wall tube),

iii) limiting heat flux is 40 $watts/cm^2$.

Thermal heat flux, first stage boiling Q_{b1} = 10/0.1884 = 53 kW/m^2 = 5.3 watts/cm^2. The heat flux is approximately 1/8 the limiting heat flux.

c) Heat Transmission Along the Heat Pipe

Assume: i) First stage tube is 5 cm dia along the complete length,

ii) limiting heat flux for transmission along the tube is 15 kW/cm^2.

Cross-section area of tube = $\pi/4 \times 5^2$ = 19.62 cm^2. Transmission heat flux = 10/19.62 = 0.5 kW/cm^2. The heat flux is approximately 1/30th the limiting value.

Assume second stage tube, 2.5 cm diameter is inserted in the first stage tube. The cross-section area of the first stage annulus is: $\pi/4\ (5^2 - 2.5^2)$ = 14.7 cm^2. The transmission heat flux is 10/14.7 = 0.68 kW/cm^2. This is approximately 1/20th the limiting value.

d) Condensing Heat Flux, First Stage

Assume: the second stage tube, 2.5 cms diameter is inserted axially concentric in the first stage tube, 5 cms diameter. The *outside* of the smaller tube contained within the larger (first stage tube) is the condensing section of the first stage. Therefore, by definition, the length of the first stage condenser is the same length as the second stage boiling section, on the inside surface of the second stage tube.

The condensing heat flux is greater than the boiling heat flux therefore we consider the second stage boiling section to determine the length required.

e) Boiling Heat Transfer, Second Stage

Assume: i) The boiling section of the second stage tube is 2.5 cm dia. ie. the inner area of the first stage condensing section,

ii) limiting boiling section heat flux is 40 watts/cm^2.

If the heat transfer = 10 kW = Q_{b_2} x A, then A = $10,000/Q_{b_2}$ = πdL, or L = 10,000/40 x π x 2.5 = 31.8 cm. We decide arbitrarily to select a second stage boiling/first stage condensing tube length of 60 cms, (about twice the limiting length to transfer 10 kW).

f) Condensing Heat Transfer, Second Stage

Assume: i) Second stage condensing tube to be stainless steel type 316 tube, thin wall, 2.5 cm diameter,

ii) limiting heat flux to be 160 watts/cm^2.

Internal area of condenser tube per m = π x 2.5 x 1 = 7.65 cm^2.

Length of tube required to transmit 10 kW, L = 10,000/160 x 7.85 = 7.96 cm.

Allow a length of 25 cms, about thrice the minimum length to transfer 10 kW.

g) Convective Heat Transfer From Outside Second Stage Condensing Section to the Cooling Water

Assume: Second stage condensing tube to be enclosed within a double wall sleeve containing running water coolant. The annulus between the condensing tube and the cooling sleeve can be a) evacuated, b) filled with argon (low thermal conductivity) and c) helium (high thermal conductivity) to provide a variable conductance system. In the limit assume a conservative maximum convective heat transfer coefficient of 1 kW/m^2 and a temperature difference, (condensing sodium, 550°C) mean water temperature 50°C) of 500°C. Then limiting heat flux is 500 kW/m^2.

If the tube is 2.5 cm diameter then to transfer 10 kW we shall

need a length of: $L = 10 \times 100/500 \times \pi \times 2.5 = 0.25$ m, 25 cm.
We shall arbitrarily choose a length of 60 cms, over twice the limiting length and equal to the length of the boiling section.

h) Condensing Heat Transfer, First Stage Thermal Dump

Assume: Maximum heat flux to be dissipated in thermal dump is 10 kW with no heat transfer to second stage. Use a variable conductance water-cooled heat exchanger identical to that for the second stage condensing section (see g above).

i) The adiabatic sections of the second stage may be arbitrarily chosen for design, manufacturing and test convenience.

3.2 Heat Input

The above design presumes a thermal input to the heat pipe from a fluidised bed but for the prototype single tube system a simpler method of heat input is proposed using an electrically heated, molten aluminum bath. This is illustrated in Figures 1, 2 and 3. The lower end of the 5 cm first stage heat pipe is sheathed by a 7.5 cm diameter stainless steel tube closed at the lower end and open at the top.

Mineral insulated, nickel jacketed electrical resistance heaters are coiled around the lower, boiling, section of the first stage heat pipe and sheathed by the outer tube. Aluminum fills the annulus separating the inner and outer tubes. Aluminum melts at a convenient temperature of 660°C, is relatively stable, safe to use, cheap and readily available and does not react vigorously with sodium or stainless steel.

Variac variable voltage transformers are used to control the voltage applied to the electrical resistance heater and so regulate the temperature and heat transfer to the first stage.

3.3 Thermal Insulation

Pre-formed aluminum jacketed mineral insulation is used around the outer tube of the molten bath, around the adiabatic sections of the second stage heat pipes to minimise extraneous heat losses and for protection around the water cooled condensing actions.

3.4 Wick Structure

The 'wick' of a heat pipe is the wire mesh or other high surface area porous lining of the heat pipe tube. It uses surface tension capillary forces to induce the return of liquid from the condensing region to the boiling region.

When the condensing region is located above the boiling region in a normal gravity environment the difference in density between the vapour and liquid is sufficient that gravity alone will ensure the return of the liquid condensate to the lower boiling region. A wick is then not required and the heat pipe is referred to as a 'thermo-syphon'.

For the two stage single tube unit described above a wick is not necessary to return the condensed liquid to the boiling region but partial wicks are included in the first and second stage boiling regions. They utilise capillary forces to ensure uniform distribution of the sodium liquid around the boiling surfaces, i.e. 'wetting' of the surfaces.

In both the first and second stage boiling regions the capillary structure proposed consists of two layers of Type 316 stainless steel industrial wire clothor woven mesh screen having 200 x 200 meshes per 25 cms and a wire diameter of 0.05 mm.

It is important to ensure the wick form is in close contact with the heat pipe wall in the evaporative section. The best way to

achieve this with stainless steel wire cloth on a stainless steel tube wall is by diffusion bonding carried out in a vacuum furnace at temperatures of 1150 to 1200°C. The length of the proposed heat pipe makes this procedure impractical with the vacuum furnaces generally available.

Another successful procedure, spot welding, is frequently similarly impractical for a long wick mounted within a relatively small bore tube unless specially designed equipment is available.

Therefore, for both the first and second stage internal wicks the light mesh capillary structure will be strengthened by a coarse 100 mesh (0.1 mm wire diameter) located at the inner radius. The three meshes will be assembled and machined rolled simultaneously on a mandrel slightly greater in diameter than the internal diameter of the tube. The inherent springiness of the mesh, particularly the coarse screen, will assist in retaining the wick against the tube wall. This will be further reinforced by long internal helical coil springs running the whole length of the first and second stage boiling section. The spring will be formed for Type 316 stainless steel wire, 2 mm diameter, coiled on a mandrel to a diameter smaller than the internal diameter of the first stage tube containing the tri-mesh tube. The coiled wire spring having a pitch of 15 mm will be inserted in the boiling section of the tube while clamped in the mandrel and then released in its final location to spring off the mandrel so pressing the wire cloth against the tube wall. This procedure is recommended by Dunn and Reay (1978) based on experience with various sodium heat pipes at the University of Reading.

3.5 Gas Ballast Reservoir

Ballast gas reservoirs are provided at the upper end of the test unit shown in Figure 1. The reservoirs, 25 cm lengths of stainless

steel tubing, 5 cms outside diameter, with end caps for sealing are provided with a combined pressure/vacuum gauge, a needle stop valve and a coupling to both argon gas and vacuum systems.

3.6 Instrumentation

The purpose of the test unit shown in Figure 1 is simply to demonstrate the ability of the unit to transmit 10 kW of heat with a maximum temperature not exceeding 800°K.

To this end instrumentation will be provided to:

a) measure the electrical power input to the electric resistance heaters of the molten bath,

b) temperature increase and mass rate of flow of the cooling water passing through the second stage condenser unit and the first stage thermal dump,

c) temperatures of the first stage and second stage tube outer walls at the following points:

   i) first stage: at a point just above the molten aluminum surface in the heater bath,

   ii) second stage: at a point just above the second stage evaporator where the second stage emerges from the first stage.

4.0 TEST AND EVALUATION PROCEDURE

4.1 Fabrication

Fabricate the heat pipe as shown in Figures 1 through 6. Do not mount in the test fixture shown in Figure 2.

4.2 Cleaning

Clean the fabricated system using the sequential procedure outlined in item 2.1 of Appendix 1 including the heated outgassing and leak testing processes. Repair leaks and continue until satisfactory leak-tight performance is obtained.

4.3 Filling

Mount the two stage unit in the test fixture bolting the securing flange to the underside of the glove box so the heat pipe is entirely supported by the securing flange.

Attach the sodium filters to the flanges of the upper gate valves and load the sealed bars of sodium metal into the glove box.

Evacuate the glove box and test for leaks.

Fill the glove box with argon gas at approximately 1.1 bar pressure. Open the gate valves of the first and second stages of the heat pipe.

Using an industrial hot air blower melt the sodium through the filters and allow the metal to enter the heat pipes. The mass of metal is not critical provided the minimum mass necessary to entirely wet the evaporator section is included. Calculations for the minimum mass for the first and second stages are included in Appendix II. A 400% excess is recommended so the mass of sodium required is:

a) First stage - 100 grams

b) Second stage - 25 grams

It is possible the liquid sodium entering the first stage will fall through the tube of the thermal dump unit and 'freeze' in the cross-tube coupling the thermal dump unit to the first stage unit. Auxiliary heating of the tube by an industrial hot air blower may be necessary

to ensure the sodium flows into the first stage.

4.4 Seasoning

Dr. G. Rice of the University of Reading has noted that sometimes a 'seasoning' process of several hours is required before a new heat pipe operates in a satisfactory manner. Rice recommends heating the unit gradually over a period of several hours with progressive increase in temperature until stable and satisfactory operation has been achieved.

4.5 Testing

The primary purpose of the two stage single tube heat pipe described above is to provide design, fabrication and operating experience with large sodium heat pipes prior to the design and fabrication of a twelve tube unit of 120 kW capacity required for integration with a Stirling air engine and a coal-fired fluidised bed combustor.

The principal testing required to accomplish this objective is then to measure: a) the electrical supply to the resistance heaters of the molten aluminum bath constituting the source, b) the heat rejected to the cooling water of the second stage condenser unit (by measuring the temperature increase and mass flow of the water).

Comparison of these two measurements will permit the 'transmission efficiency' of the heat pipe to be determined:

$$\eta_{trans} = \frac{Q_{out}}{Q_{in}}$$

Secondary testing will be carried out to demonstrate the automatic operation of the thermal dump system. This will be effected by making the second stage condenser inoperative (by evacuating the water-cooled helium gas-filled conducting annulus around the second stage condenser

tube).

Further tests will be carried out to determine the effect of the argon gas pressure on the location of the argon/sodium vapour interface as a function of temperature, and yet further work to determine the temperature loss at the first stage condenser/second stage evaporator.

4.6 Problem Areas

There appears to be no insuperable problems to the fabrication and operation of the single tube, two stage heat pipe described above and the application of the same principles to very much larger multi-tube units.

It should again be made clear these observations are not based on practical experience. Furthermore no published reports were located of experimental work on two stage heat pipes.

Again the size level (10 kW thermal capacity) is substantially greater than the majority of heat pipes constructed to date and may approach the upper limit of practical accomplishment.

In these circumstances the fabrication and testing of the proposed unit should be viewed more as a research investigation than routine engineering work.

The experience of others with smaller heat pipe units suggests the principal problem areas to be anticipated are:

a) difficulties in the acquisition of stainless steel tubes and billets free of minute defects, cracks, occlusions, etc.

b) the achievement of welds of the necessary high quality. Tungsten inert gas (argon-arc) welding is the preferred process. Electron beam welding is not practical because the large vacuum furnace required is unlikely to be available.

c) achievement of the degree of cleanliness and purity necessary to prevent corrosion or chemical degradation.

d) proper distribution of liquid sodium metal over the entire length of the 'wick' in the first and second stage evaporative sections. This is related to the 'seasoning' process discussed above. Techniques to promote 'wetting' of stainless steel surfaces by sodium metal and the prevention of 'dryout' in subsequent operation appear to be imperfectly understood.

5.0 CONCLUSION

There is no apparent intrinsic limit to the size or capacity of sodium heat pipes but practical experience in the field is limited. A research project to construct and test the two stage unit described should be undertaken herein.

REFERENCES

Anon. Proceedings International Heat Pipe Conference

1st - 1973 - Stuttgart, F.R., Germany

2nd - 1976 - Bologna, Italy

3rd - 1978 - Palo Alto, Calif., U.S.A.

4th - 1981 - London, England

5th - 1984 - Tsukuba, Japan.

Anon. Engineering Sciences Data Unit 251-259 Regent St., London, W1R7AD

a) Folio 79012: Heat Pipes - Performance of Capillary-Driven Designs

b) Folio 79013: Heat Pipes - Properties of Common Small-Pore Wicks

c) Folio 80013: General Information on Heat Pipes

d) Folio 80017: Thermophysical Properties of Fluids for Heat Pipes in the Temperature Range - 60°C/300°C

e) Folio 81038: Heat Pipes: Performance of Two-Phase Closed Thermosyphons.

Asselman, G.A.A. and Green, D.B. (1973 a and b). Heat Pipes. Pt. I - Operation and Characteristics, Philips Tech. Rev., 33(4), pp. 104-113; Pt. II - Applications, Philips Tech. Rev., 33(5), pp. 138-148.

Asselman, G.A.A. (1976). Fluidised Bed Coal Combustion as a Heat Source for Stirling Engines. Proc. 11th IECEC, Lake Tahoe, Nev., Sept. 12-17.

Barton, D.W. and Holcomb, R.S. (1982). Private Communication. Oak Ridge National Laboratory, Tennessee, U.S.A.

Dunn, P.D., Rice, G. and Thring, R.H. (1975). Hydraulic and Rotary Drive Stirling Engines with Fluidised Bed Combustion/Heat Pipe System. Proc. 10th IECEC, pp. 942-947, Paper No. 759141, Newark, N.J., Aug. 17-22.

Dunn, P.D. and Reay, D.A. (1978). Heat Pipes. Pergamon Press Ltd., Oxford, England.

Lyon, R.N. (Editor). (1952). Liquid Metals Handbook. Atomic Energy Commission/U.S.A. Navy NAVEXDS P-733, U.S.A. (NTIS, Springfield, Va.).

Rice, G. (1983). Private Communication, University of Reading, School of Engineering, U.K.

Rice, G. and Jennings, T. (1973). Heat Pipe Filling. Proc. 1st Int. Heat Pipe Conf., Stuttgart, F.R. Germany.

Thring, R.H., (1975). Fluidised Bed Combustion for the Stirling Engine. Ph.D. Thesis, Reading University.

Walker, G. (1980). The Stirling Engine for Railway Locomotive Application. Report No. TP 2930E, Transportation Development Centre, Montreal.

APPENDIX I *

HEAT PIPE FILLING

G. Rice and J. D. Jennings,
Reading University, Reading, England.

1. Introduction

Liquid metal heat pipes have been developed at the Applied Physical Sciences Department of Reading University for both nuclear and Stirling engine applications. Water charged heat pipes have been developed for electronic cooling systems.

2. Construction of sodium charged heat pipes

A few of the basic cylindrical geometry heat pipe designs are illustrated in figure 1. Crimp sealing, figure 1a, was used for early heat pipes but was found to be unsatisfactory above a temperature of 450°C. A plug sealing technique was developed but the early design, figure 1b, proved difficult to perfect. The latest design of plug seal is shown in figure 1c. In each design the pipe was made of type 321 (EN 58B) stainless steel seamless tube of 2.5 cm diameter by 0.9 mm wall thickness. The capillary structure consisted of two layers of 100 mesh stainless steel having a wire diameter of 0.1016 mm and an aperature size of 0.152 mm.

2.1 Cleaning, fabrication and filling

The following cleaning process is adopted.

i Wash with water and detergent.
ii Rinse with demineralised water.
iii Soak in 1/1 mixture of H Cl acid and water for 30 minutes.
iv Rinse with demineralised water.
v Soak in acetone (in ultrasonic bath) for 20 minutes and repeat with clean fluid.

The procedure is repeated after completion of welds and brazed joints - during the fabrication process. Argon arc welding is used throughout and the finally fabricated heat pipe is evacuated to a pressure of 10^{-5} torr and after satisfactory leak testing the pipe is outgassed at a temperature of 200°C for several hours in order to remove condensable gases and vapours. Heating is effected by immersion of the pipe in liquid paraffin - which is electrically heated.

Liquid metal may be charged into the heat pipe by any of the following three methods:

(a) Distillation of metal into the pipe, with the pipe kept relatively cold to effect condensation onto the walls and capillary structure.

* The work was undertaken under a S.R.C. award.

(b) The liquid metal is initially contained in a glass ampoule which is placed in the filling and evacuating tube of the heat pipe. The ampoule is broken by distortion of the filling tube. The charge released from the ampoule will run into the heat pipe when the filling tube is heated to raise its temperature to the melting point of the liquid metal.

(c) Liquid metal, in its "raw state", is contained in a glass filter tube which is attached to the filling tube of the heat pipe. A by-pass to the filter allows for pre-evacuation and final outgassing of the heat pipe. The filling device and heat pipe are immersed in liquid paraffin which is heated (electrically) to enable the liquid metal to be raised in temperature to its melting point. The arrangement is illustrated in figure 2a. The by-pass valve is finally closed in order to apply gas pressure (helium) to the molten solium to help force it through the filter - for the charge to run finally into the heat pipe.

Method (c) is the one more generally adopted at Reading to date. Serious doubts exist however regarding the purity of filtered metal and the effect of possible contamination causing eventual failure of operation of the heat pipe due to blockage of the wick structure. This method of filling is however simple to adopt and is probably acceptable where the heat pipe is to be operated for short life only. Distillation methods are favoured when long life is required (i.e. thousands of hours).

2.2 Sealing of heat pipe

Several techniques exist for the final sealing of the heat pipe, certain of which however pose limitations in final operating conditions of the pipe. Possibly the simplest technique is crimping of the filling tube, see figure 1, and a modified "bolt cropper" has been used successfully for this operation. Crimping can however only be achieved successfully, to provide vacuum tight seals, with ductile tube material such as copper. The final cutting action of the crimp must cause welding of the material at the knife edge. This weld, while vacuum tight, is not very strong. Alternative sealing techniques are illustrated in figure 1. Spot welding across a flattened section of the filling tube, figure 1d, by electric discharge, has proved unsuccessful. Attempts have also been made to seal by combined cutting and welding by argon arc across a flattened section of the tube, but this also has proved abortive. A further method of sealing is shown in figure 1e, where a tapered pin is hammered into the filling hole of the end connection of the pipe - to effect a 'cold weld'. The vacuum adaptor, required for this operation, is then removed and the pin is cut and finally welded to the end cap, as illustrated. This technique, while of proven success, is complex - especially in view of filling difficulties.

The latest development has been the technique of plug sealing, see figure 1c. A special rig has been constructed which allows for outgassing of an open ended tube and sodium filling

by the filtering method described above. On completion of the filling process the end sealing plug, supported by a swivel arm within the filling chamber, is swung into position and placed within the heat pipe. The plug is then induction heated to effect a brazed vacuum seal. The apparatus and sequence of operation is illustrated in figure 2b. The end sealing plug is finally argon arc welded - after removal of the heat pipe from the filling apparatus. 36.

3. Capillary structure

The integrity of the wick structure is essential for achieving proper capillary action. In the case of use of wire mesh it has been discovered that best results are achieved if the structure (one or more layers) is welded intermittently to the wall of the pipe and a special tool was built for this purpose. The results of operation of sodium charged heat pipes, reported below, refer to use of this technique with two layers of mesh.

Alternative wick structure are available and an arrangement which perhaps offers the best results is the composite type. The wall of the pipe is grooved for good axial transfer of working fluid while a mesh structure covering the grooves provides the necessary capillary pumping. An early attempt at Reading to achieve such an arrangement was to "broach" grooves into the tube. The tube is retained in a mandrel in order to prevent distortion of the wall while drawing the broaching tool through the tube. The tool was designed to provide grooves 0.1 mm wide by 0.66 mm deep, spaced at 0.3 mm cut in a stainless steel tube of 2.5 cm diameter and 8.9 mm wall thickness. Unfortunately the tool showed a rapid rate of wear and the grooves were of irregular size and configuration. It proved impossible to obtain capillary action by the grooves alone but the technique offers a solution for providing composite capillary structure, with wire mesh, when plain tube only is available.

It has been discovered that wetting of the mesh structure, by sodium, is not readily achieved until the heat pipe is heated as a thermo-syphon for several hours at 650°C. Speculation exists regarding this activating process and could be due to reduction of Cr_2O_3 or even further cleaning (degreasing) by the Na at high temperature.

4. Operation of sodium-stainless steel heat pipe

In the early heat pipe design the end connection (copper crimp) had to be protected by buffering with helium. The heat pipe, which was 90 cm long by 2.5 cms diameter, was charged with helium to a pressure of 20 torr. The pipe was heated by an R.F. coil over a length of 10 cm and temperatures were measured by chromel-alumel thermocouples which were monitored by a potentiometric recorder. The temperature profiles resulting from heat inputs of 1.2 kW and 1.4 kW are shown in figure 3. It may be noted that the buffered length (L-x) is approximately proportional to the power input. In checking the vapour pressure corresponding to the observed temperature of the isothermal region there is seen to exist good correlation with the ratios of buffer lengths to gas and

vapour pressures at the varying heat inputs. There was no measurable difference in temperature of the tube between the adiabatic and condenser regions. It may therefore be inferred that there was negligible temperature difference between the vapour and tube.

The maximum length of heat pipe operated vertically below the heat input section was 30 cms. Start-up in this heat pipe mode of operation was much steadier than when operating as a thermosyphon, i.e. with the pipe vertical and heated at the bottom, when there is a rapid fluctuation in temperature due to violent boiling action of the fluid. This action is obviously due to excess liquid in the pipe, while in the case of operation in the heat pipe mode the excess liquid is situated below the evaporator region.

The latest plug seal design of heat pipe has allowed for high temperature operation over the whole length - with no buffering. The test apparatus is not yet fully developed since it does not include calorimetry for control and accurate estimation of the heat received at the condenser region. It should be noted that the heat input values given in figure 3 are derived from calibrated R.F. heater output and checked by radiation and convection heat transfer calculations.

5. Water charged heat pipes

The construction of a water charged copper tubed heat pipe is extremely simple but incorrect monitoring of the liquid charge can lead to severe limitations in performance. There exists also a safety consideration if overheated.

5.1 Construction of heat pipe

A simple copper tubed heat pipe is illustrated in figure 4. The correct amount of fluid should be injected before sealing and techniques adopted for this purpose are also illustrated in the figure. The tube may be sealed by crimping of the filling tube or by an end plug - which is brazed into the tube under vacuum while the liquid charge is frozen within the pipe.

5.2 Operation of water charged heat pipe

A heat pipe made of 7.8 mm inside diameter by 0.9 mm wall thickness copper tube and having a wick consisting of 2 layers of 100 mesh phosphor bronze was charged with distilled water, using method (b) as illustrated in figure 4. The water charge was frozen and the pipe evacuated to a pressure of 0.1 torr before the final crimp seal. The heat pipe was tested by use of an electrical resistive heater element to evaporate over a length of 5 cm, and an air cooled calorimeter was used to condense over a length of 5 cm, each situated as shown in figure 5. The resultant vapour and wall temperatures for varying heat input are presented in figure 5. The results refer to operation of a pipe containing 200% excess liquid charge. The temperature difference between the vapour and the condenser surface is seen to increase with heat input.

The tests were repeated with reduced water charge and the temperature difference between the vapour and condenser wall was reduced. This clearly illustrates the effect of temperature reduction due to the presence of a liquid film over the condenser surface due to excess liquid charge. A secondary reservoir within the condenser region of the pipe alleviates this problem. This reservoir would consist of a capillary structure having a larger pore size than that of the main wick structure of the pipe. For the heat pipe results presented in figure 5, the reduction of fluid charge was achieved by addition of a 60 mesh reservoir structure compared to 100 mesh for the heat pipe wick. This method of excess fluid absorption within the pipe, has also been proposed by B.D. Marcus (1).

6. Discussion

The filling and sealing of liquid metal heat pipes is likely to continue to require the use of complex apparatus. For long life applications it is considered advisable to use distilled metal charge which may be injected direct into the heat pipe or first into an ampoule for final charging by a method similar to that presented in this paper for filtered sodium. Several sealing techniques exist and the authors favour the plug sealing method for containment of low vapour pressure fluids - because of the positive nature of the seal. On no account however should plug sealing be used for commercially sold heat pipes having a high vapour pressure fluid - such as water. Overheating of such a pipe could cause ballistic ejection of the end plug. A crimp or alternative low bursting pressure seal should be used for such fluids. With low conductivity working fluids the quantity of charge must be accurately metered to avoid large temperature gradients at the condenser. Introduction of a secondary reservoir does however offer a solution to this problem. This factor is illustrated by comparison of the results of operation with sodium (figure 3) to water (figure 5) which vary significantly in thermal conductivity and in the case of water the excess liquid at the condenser can lead to a considerable temperature gradient.

References

(1) B. D. Marcus, "Theory and Design of Variable Conductance Heat Pipes", TRW Systems Group under NASA contract NAS 2 - 5503, publ. NTIS report no. N72-23953. (Unclas. H1/33 27887) April 1972.

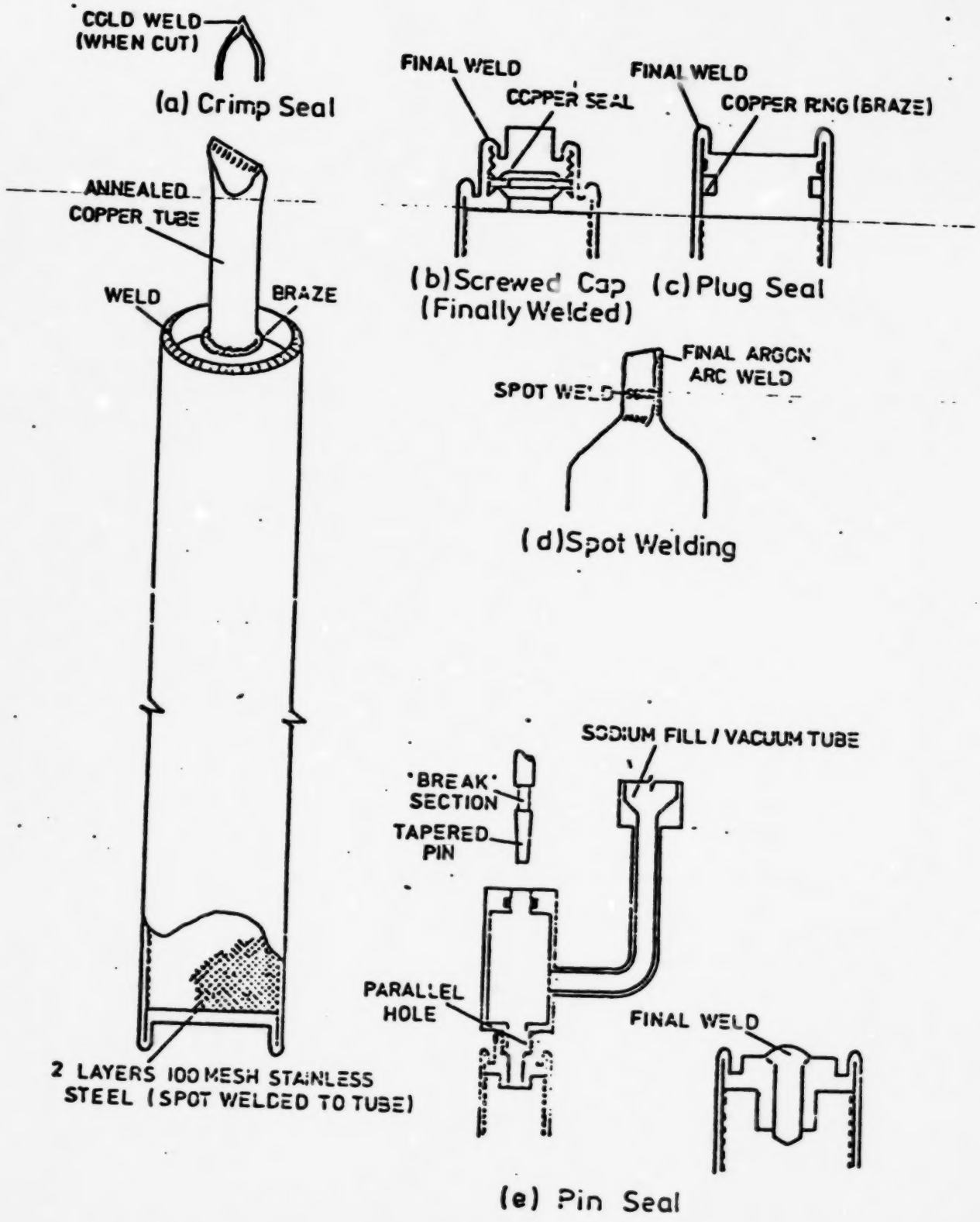
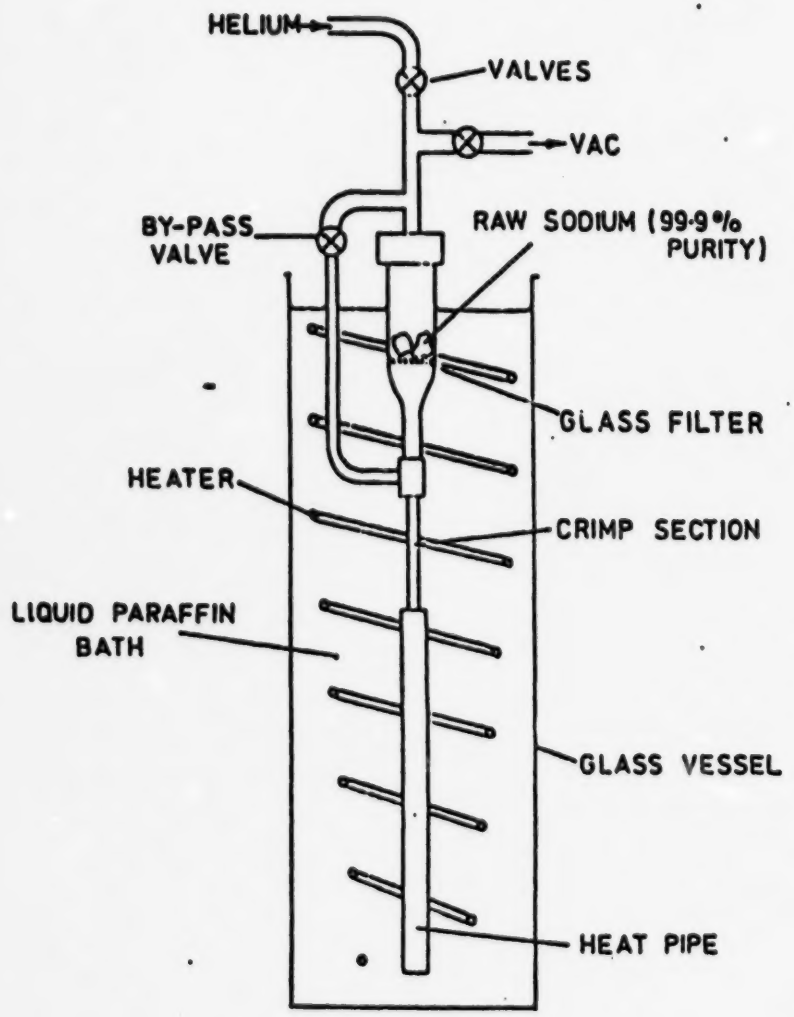
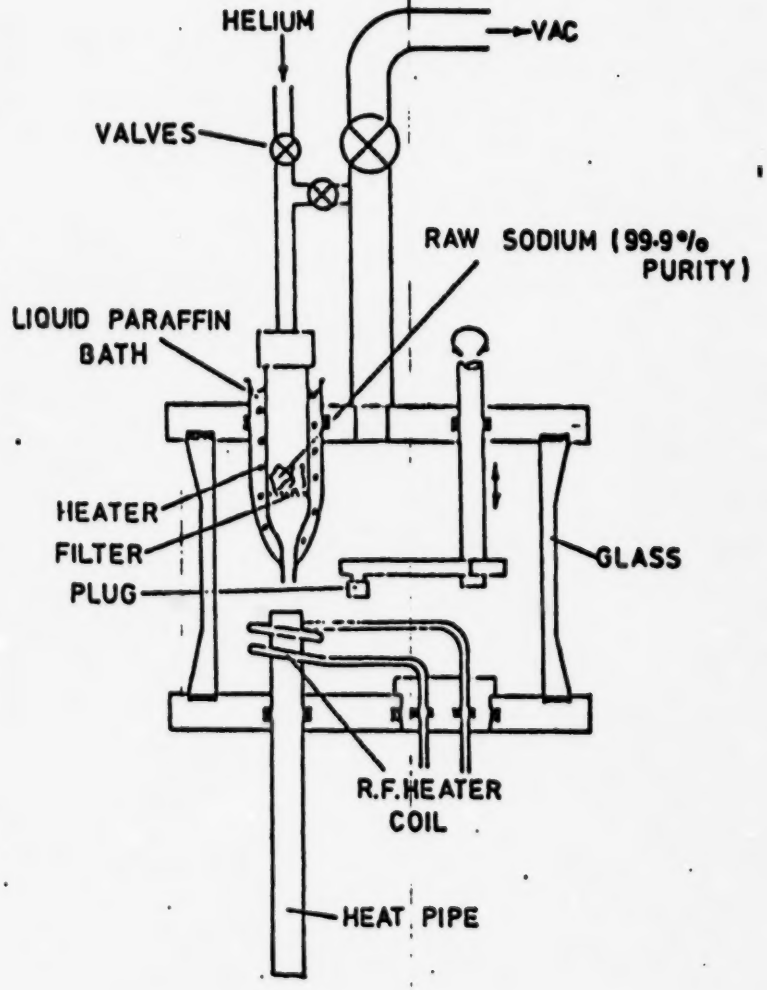


Fig. 1 Alternative methods for the sealing of heat pipes



Method (a)



Method (b)

Fig. 2: Arrangements for filling of heat pipes

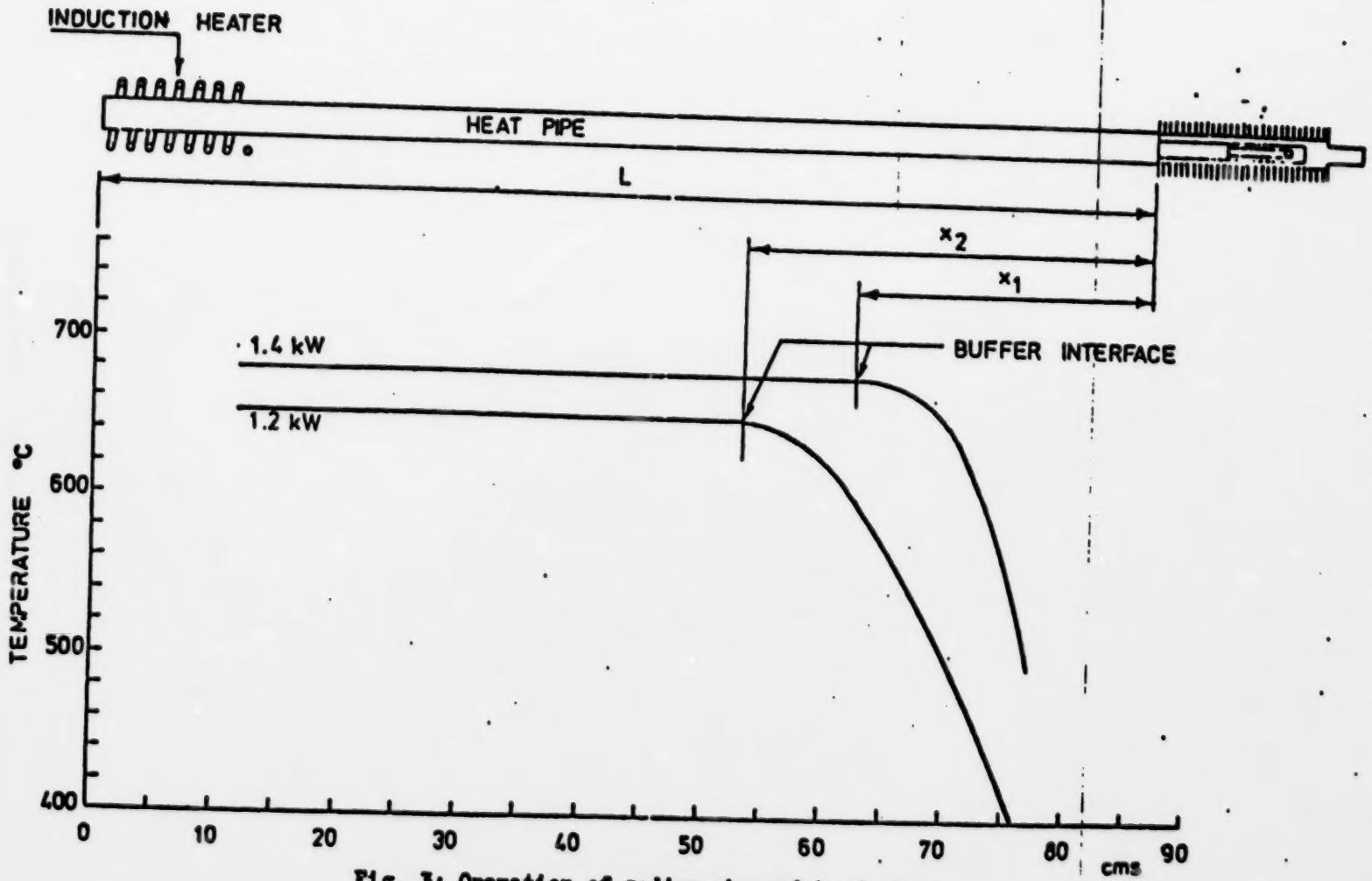


Fig. 3: Operation of sodium charged heat pipes

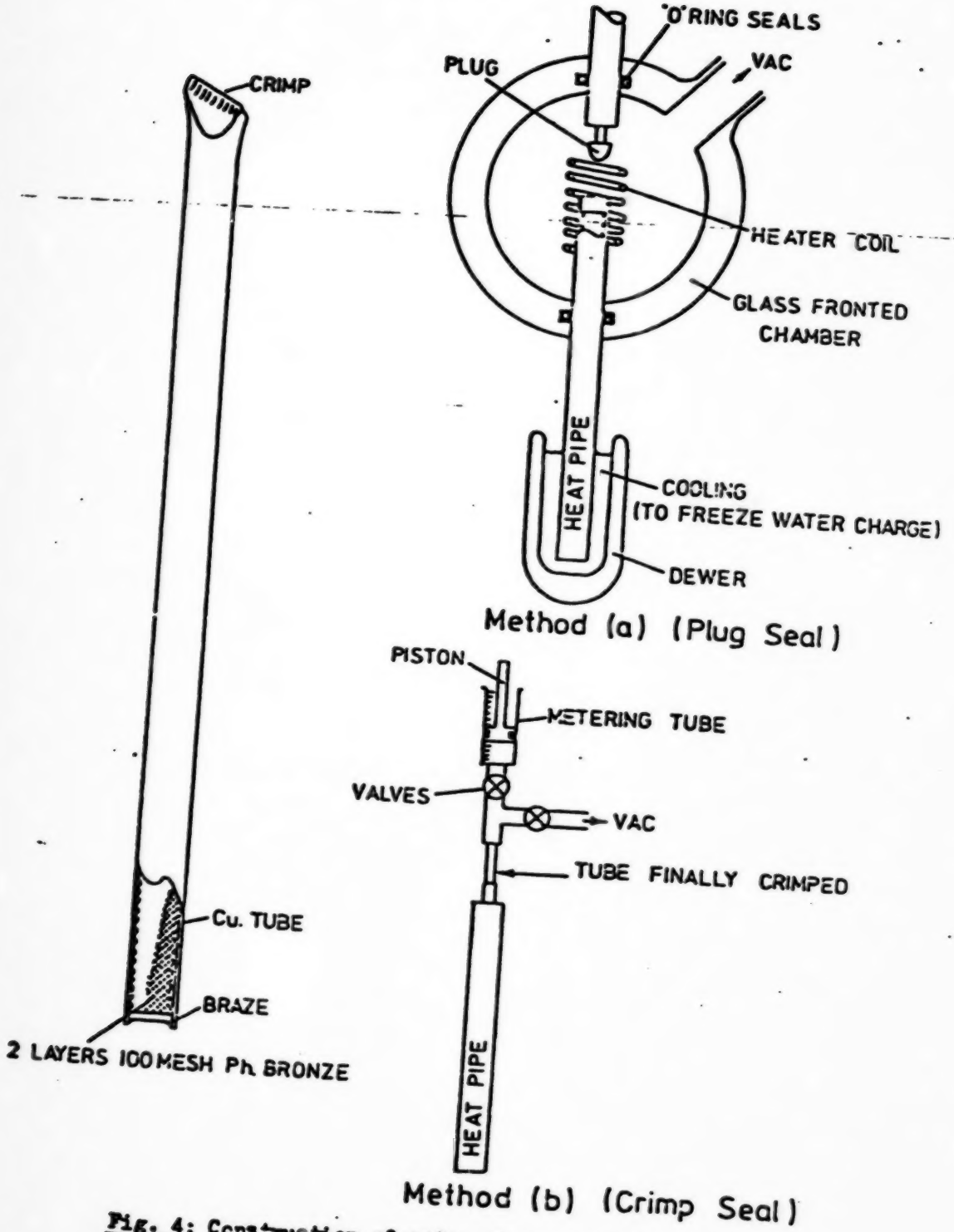


Fig. 4: Construction of water charged heat pipes

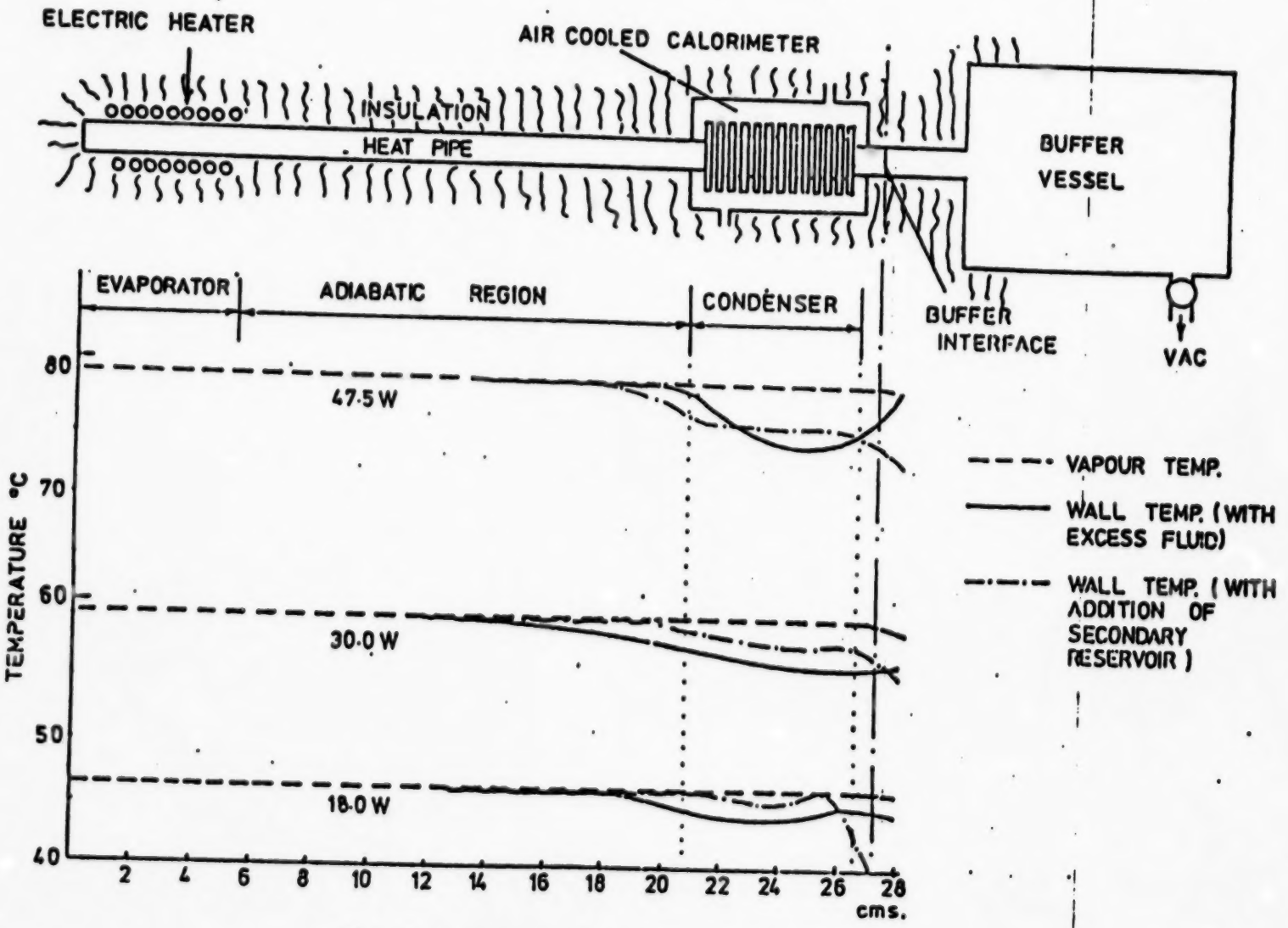


Fig. 5: Operation of water charged heat pipe

APPENDIX II

CALCULATION OF SODIUM MASS

First Stage: Metal required to fill the wick structure.

Wick consists of 2 layers of 200 mesh stainless screen. Wire diameter is 0.05 mm, screening area is 37% (assume porosity is 63%). The wick is 1.2 m long, width is (π x 5) cms and the thickness is (2 x 0.05 x 2) mm.

The porous volume of the wick is then: 0.63 x 120 x π x 5 x 4 x 0.005 = 23.73 cm^3. The density of sodium at 100°C is 0.928 g/cm^3 (Lyon, 1952, p. 42). The mass of sodium required to fill the wick is therefore 0.928 x 23.73 = 22 gms.

If we allow a 400% surplus capacity the required mass is 4 x 22 = 88 grms, say 100 gms.

Second Stage:

The wick consists of 2 layers of 200 mesh stainless screen, wire diameter 0.05 mm, screening area 37% (assume porosity is 63%), 60 cms long, width π x 2.5 cms, thickness 2 x 0.05. The mass of sodium required is one quarter that required for the first stage heat pipe. The required mass is therefore 100/4 = 25 gms.

Centre de développement
des transports
1000 o., rue Sherbrooke
Suite 2421
Montréal, Québec
H3A 2R3

Transportation
Development Centre
1000 Sherbrooke St. W.
Suite 2421
Montreal, Quebec
H3A 2R3

POOR

QUALITY

ORIGINAL